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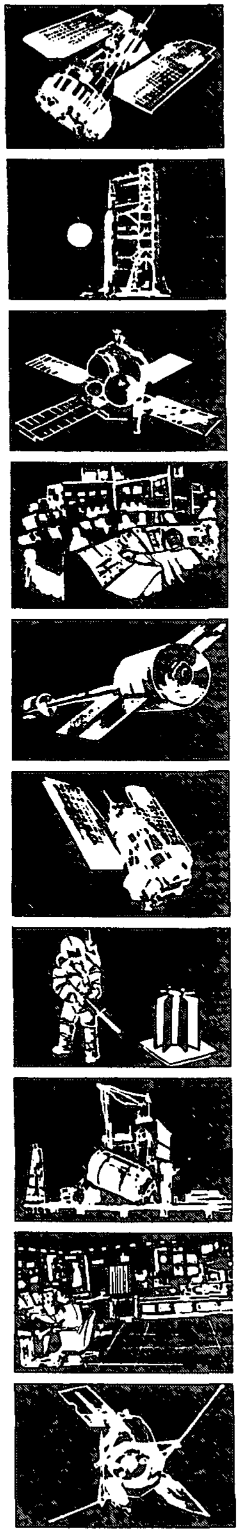

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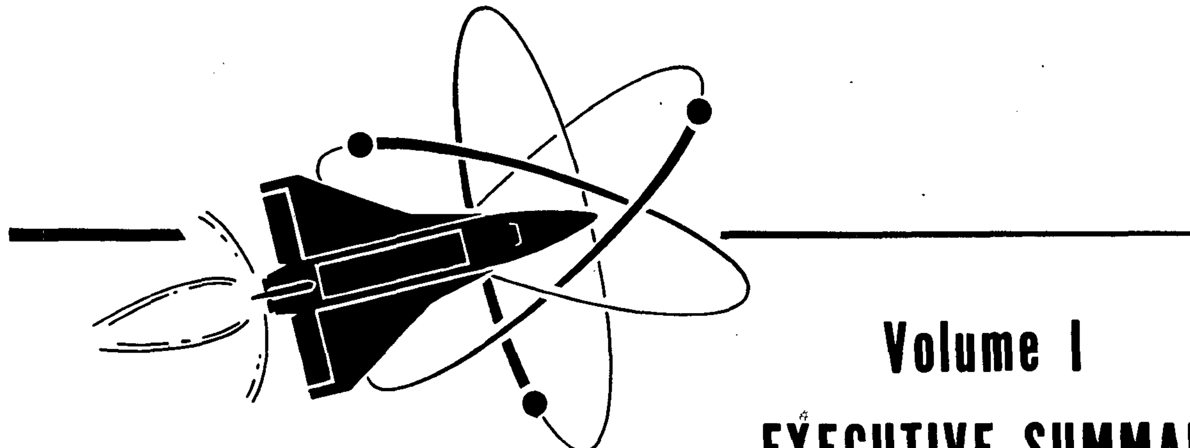
JANUARY 1972

manned space flight nuclear system safety



Volume I
EXECUTIVE SUMMARY

Part 2
SPACE SHUTTLE NUCLEAR SYSTEM SAFETY

GENERAL ELECTRIC

DOCUMENT NO. 72SD4201-1-2
JANUARY 1972

FINAL REPORT

MANNED SPACE FLIGHT NUCLEAR SYSTEM SAFETY

VOLUME I - EXECUTIVE SUMMARY

PART 2 - SPACE SHUTTLE NUCLEAR SYSTEM SAFETY

PERFORMED UNDER

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FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

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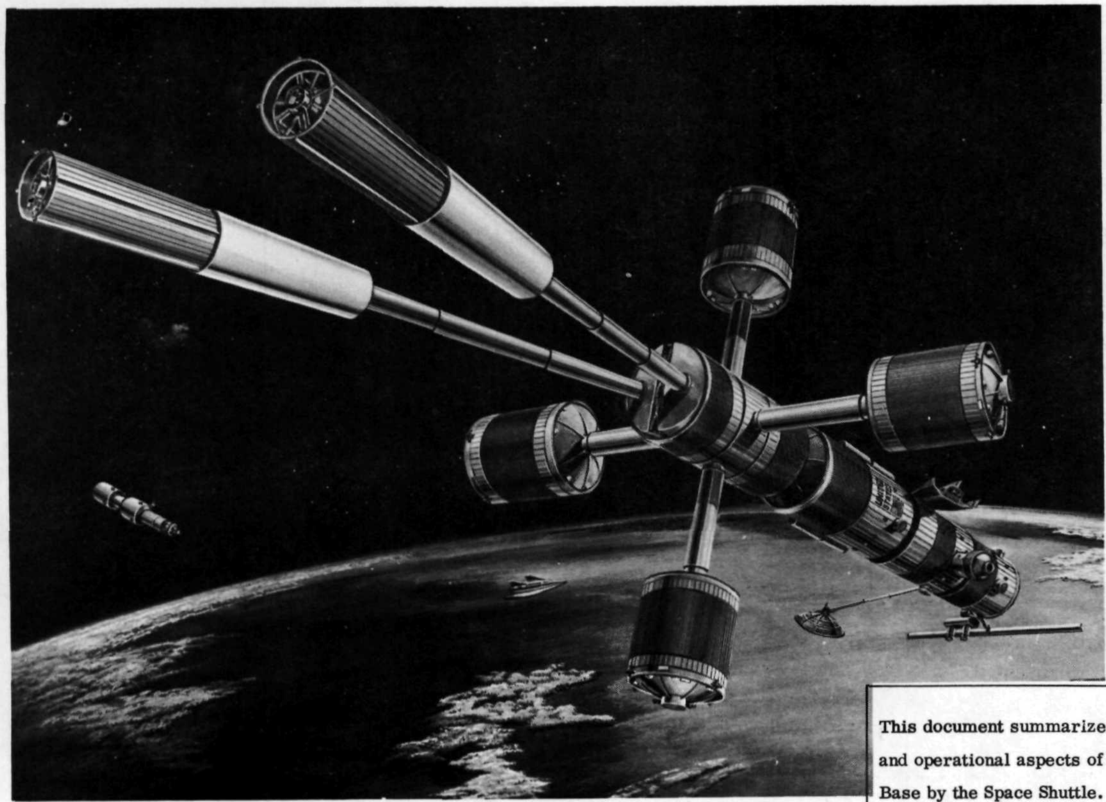

ABSTRACT

This document summarizes the results of a study addressing the nuclear safety integration and operational aspects of transporting nuclear payloads to and from an earth orbiting Space Base by the Space Shuttle. The study was performed as a part of the overall Space Base Nuclear System Safety Study summarized in Volume I, Part 1, 72SD4201-1-1.

The representative payloads considered were (1) the Zirconium Hydride reactor-Brayton power module, (2) the isotope-Brayton power module, and (3) small isotope power systems or heat sources. Areas of investigation include nuclear safety related integration/packaging and operational/procedural requirements of the Shuttle and Payload systems for all phases of the mission (launch through recovery). A preliminary terrestrial safety evaluation was also performed. Results of the analyses indicate (1) the need for a transfer module to minimize the integration impact on all systems, (2) no additional shielding is required for the crew in transport of a clean reactor, (3) the blast and fragmentation environment of the Shuttle is severe - the positioning of the payload away from the Mobile Launcher tower will reduce fragmentation damage, and (4) use of the Shuttle for retrieval and recovery of nuclear payloads can result in a low risk to the general populace.

The nuclear safety guidelines resulting from the study should be considered in subsequent phases of NASA's Space Shuttle program to increase overall system safety.

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Operational and design requirements of large, long duration manned space vehicles differ from those of the Mercury, Gemini, and Apollo programs. Of particular interest are the radiation survivability and nuclear safety requirements imposed by nuclear power reactors and isotopes and the long term interaction with the natural radiation environment.

The General Electric Company under contract to NASA-MSFC (NAS8-26283) has performed a study entitled "Space Base Nuclear System Safety" for the express purposes of addressing the nuclear considerations involved in manned earth orbital missions (operational and general earth populace and ecological nuclear safety aspects). An added task addressed the nuclear safety aspects of transporting nuclear hardware to and from the Space Base by the Space Shuttle.

The study was sponsored jointly by NASA's Office of Manned Space Flight, Office of Advanced Research and Technology, and Aerospace Safety Research and Data Institute. It was performed for NASA's George C. Marshall Space Flight Center under the direction of Mr. Walter H. Stafford of the Advanced Systems Analysis Office. He was assisted by a joint NASA and AEC advisory group, chaired by Mr. Herbert Schaefer of NASA's Office of Manned Space Flight.

The results of the study are presented in seven volumes. The titles and a cross-reference matrix of the subjects covered in the various volumes is presented in the Table. on the next page.

Questions regarding these volumes may be forwarded to the following:

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Manned Space Flight Nuclear System Safety Documentation

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*Limited Distribution

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GENERAL

The Space Shuttle with boost, maneuvering, payload handling, retrieval and reentry capability is potentially a versatile and reliable transporter of nuclear hardware.

This study has investigated the nuclear safety integration and operational aspects of transporting nuclear payloads to and from an earth orbiting Space Base by the Space Shuttle. The study was performed as an additional task to the Space Base Nuclear System Safety Study which was summarized in Volume I, Part 1 (72SD4201-1-1).

The representative payloads considered were (1) the Zirconium Hydride (ZrH) reactor-Brayton power module, (2) the isotope-Brayton power module, and 3) small isotope power systems or heat sources.

Results of this study are considered applicable for design and development phases of future nuclear missions involving the Space Shuttle. Study details can be found in Volumes IV, Part 1 and 2 and Volume V, Part 2.

OBJECTIVES

The prime objective of this study is to provide a nuclear system safety investigation of the Space Shuttle as a means of transportation of nuclear systems used in conjunction with a Manned Space Base. The specific study objectives are listed in Table 1.

Table 1. Specific Study Objectives

- Determine the safety related impact of nuclear payloads on the design and operation of the Shuttle.
- Identify safety related constraints imposed by the Shuttle upon the design and integration of nuclear payloads.
- Assess nuclear hazards to the earth's populace that result from transportation of nuclear payloads.
- Establish nuclear safety and integration guidelines and procedural recommendations for use in the transportation of nuclear payloads with the Shuttle.

SCOPE

This study addresses the nuclear system safety aspects of the Space Shuttle/Space Base program including crew/personnel safety, mission success, and the impact on supporting facilities.

Mission operations considered include:

- Preparation and transportation at Launch Site
- Launch and ascent to the Space Base
- Rendezvous and docking at the Space Base
- In-orbit transfer (loading-unloading)
- End of Mission return to earth including reentry and landing
- End of Mission disposal into high orbit
- Emergency disposal
- Abort/contingency modes

The nuclear related hazards associated with the nuclear payloads are identified. Design and operational features of the Shuttle and nuclear payloads are evaluated to provide nuclear safety related payload integration considerations.

A preliminary terrestrial nuclear safety analysis is performed for the reactor and isotope-Brayton power module payloads. Means for implementing contingency operations and normal and emergency in-flight maintenance and repair are discussed. Design and operations guidelines are presented for use in subsequent phases of Space Shuttle/nuclear payload programs in the elimination reduction of nuclear hazards to the crew, support personnel and the earth's populace.

The basic ground rules employed in the study are summarized in Table 2.

Table 2. Study Ground Rules

• The reference mission is the Space Base mission supported by the Space Shuttle as defined by McDonnell Douglas and North American Rockwell for NASA MSFC, and MSC respectively.
• The Space Shuttle will be used as the transporter in the initial launch and subsequent replacement and disposal/recovery of the nuclear sources.
• The nuclear payloads to be considered will consist of complete or modularized isotope-Brayton and ZrH reactor-Brayton power modules in addition to small isotope sources. The payload configurations and operational capability are those studied by NAR and MDAC for NASA.
• The Space Shuttle baseline is assumed to be capable of handling a payload of at least 11.3 t (25 klb) to a 500 km (270 nm), 55° inclined orbit with payload dimensions of up to 4.6 m (15 ft) diameter and 18.3 m (60 ft) in length.
• Dose rate to the Shuttle crew should be minimized. Maximum dose rate to the crew from nuclear payloads is to be limited to 150 mrem/day (5 cm depth dose).

STUDY APPROACH

The Space Base safety analyses consisted of seven principal tasks as illustrated in Figure 1. The

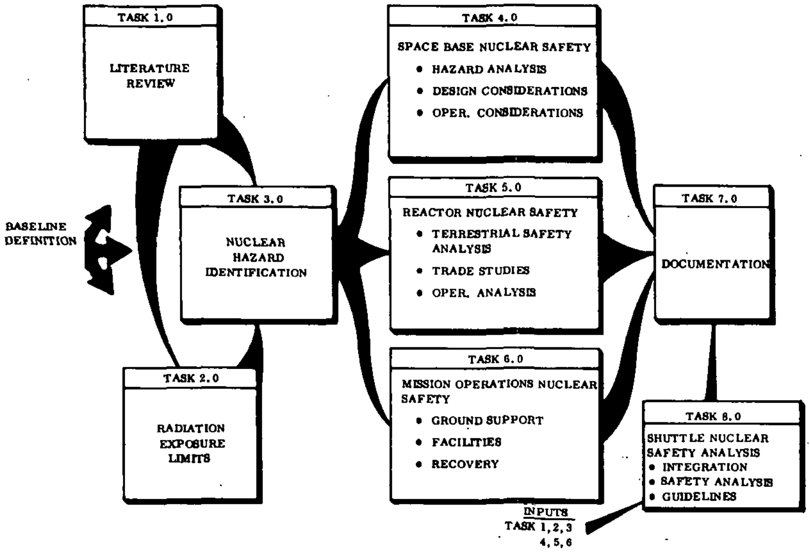


Figure 1. Study Task Structure

Shuttle nuclear safety effort (Task 8) was added during the course of the Space Base Study. Task 8 was divided into the following subtasks:

8.1 Nuclear Payload/Space Shuttle Integration

8.2 Terrestrial Nuclear Safety Analysis

8.3 Nuclear Safety Guidelines and Requirement Preparation

Subtask 8.1 involved the evaluation of designated Shuttle and payload concepts to identify the significant interface requirements to implement nuclear safety (crew, ground support personnel, equipment) during all mission phases. A preliminary nuclear safety evaluation of the nuclear payloads was performed in Subtask 8.2 with emphasis on terrestrial nuclear safety to determine the hazards and degree of risk to the general populace and ecology. Detailed failure sequence trees were developed to identify the source, probability and extent of the hazards. A contingency evaluation was performed to identify the major contingency situations and possible actions which could be taken.

The various analyses resulted in the formulation of a number of nuclear safety related guidelines. These were compiled and documented in Subtask 8.3.

REFERENCE MISSION

A reference mission was established to allow identification and analysis of operations and potential hazards and to provide a reference design against which guidelines and recommendations resulting from the study could be established and evaluated. The reference mis-

sion incorporated significant nuclear safety aspects from the Space Base and Space Shuttle studies of North American Rockwell and McDonnell Douglas.

SPACE SHUTTLE

The Shuttle can be used to transport nuclear systems from the launch pad to a Space Base in low earth orbit (typically 500 km, 55^{o} inclination), and dispose of the nuclear systems at their end of life by return to the earth's surface or injection into high earth orbit. Typical staging points of a Shuttle mission are shown in Figure 2.

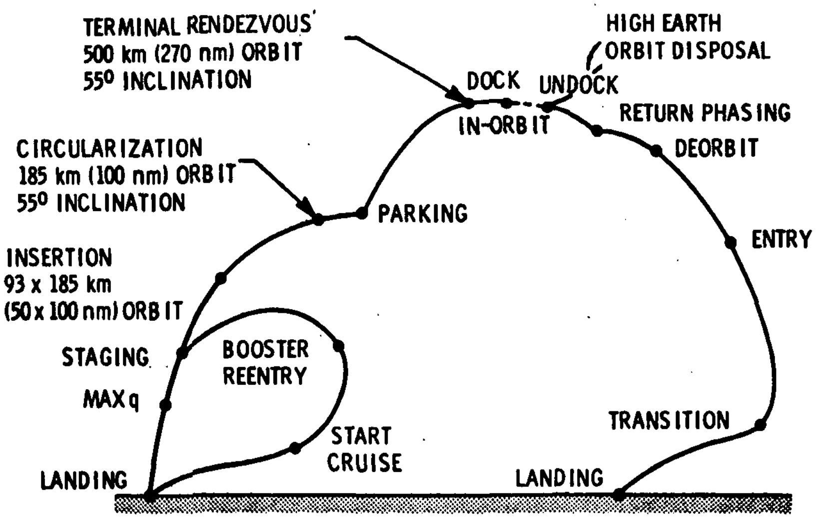


Figure 2. Shuttle Mission Staging Points

The Space Shuttle launch configuration consists of two separate vehicles, (1) a booster which provides the initial lift-off thrust, and (2) the Shuttle orbiter which carries the payload into earth orbit after separating from the booster subsequent to first stage thrust termination. Since the nuclear payload is carried inside the Shuttle, the Shuttle configuration rather than the booster was of most importance in this study. The NAR and MDAC Phase B Shuttle configurations are shown in Figures 3 and 4.

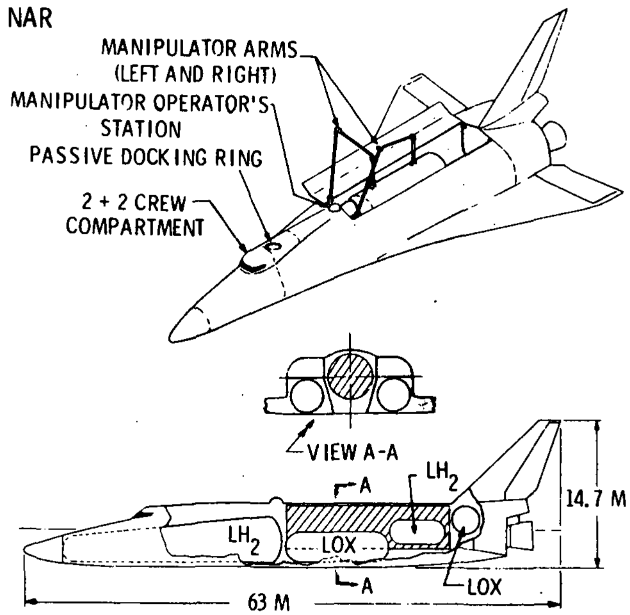


Figure 3. NAR Phase B Shuttle Configuration

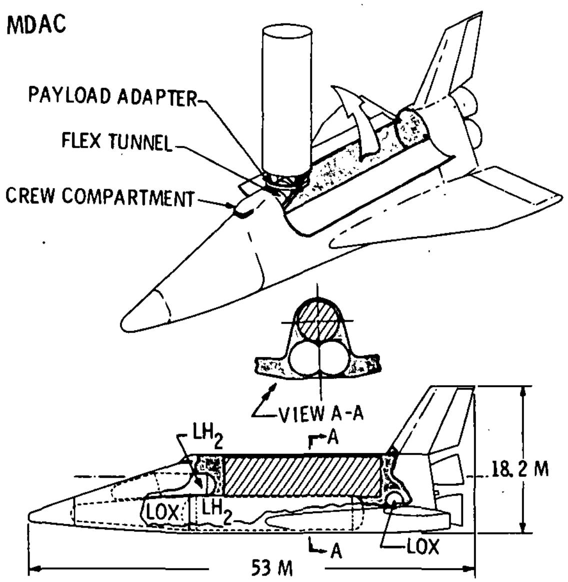


Figure 4. MDAC Phase B Shuttle Configuration

In both configurations, the cargo bay is in close proximity to the primary LH_2/LO_2 tankage. The NAR Shuttle has two crew locations - the manipulator operator's station and the pilot's cockpit, respectively. The MDAC Shuttle has only one crew location, the pilot's cockpit, located 6.1 m forward of the cargo bay.

NUCLEAR PAYLOADS

The reactor power module identified for the Space Base Study is 6.6 m in diameter and does not fit within the 4.6 m diameter Shuttle cargo bay. Therefore, the Space Station ZrH reactor power module with a Brayton cycle power conversion system was used in this study because of its compatibility with the Space Shuttle cargo bay dimensional limitations. The basic reactor is the same as that identified for the Space Base Program with the following exceptions:

1. Normal operation is at 125 kWt compared to the 330 kWt of the Space Base Program, resulting in decreased radiator area. (Transport of the Space Base power module by Space Shuttle might involve a deployable radiator or multiple Shuttle launches.)

2. The reactor/shield assembly incorporates less radiation shielding resulting in a lower mass but increased dose rates around its perimeter.

The reference reactor power system can be packaged in various configurations to maintain Shuttle compatibility. A single reactor module is illustrated in Figure 5.

The isotope-Brayton power system could consist of one or more large isotope heat sources coupled with several power conversion systems to provide the desired total electrical power output. For purposes of this study, two 52 kWt heat sources are operated simultaneously to provide 25 kWe usable power. Three configurations for the 25 kWe isotope-Brayton power system were con-

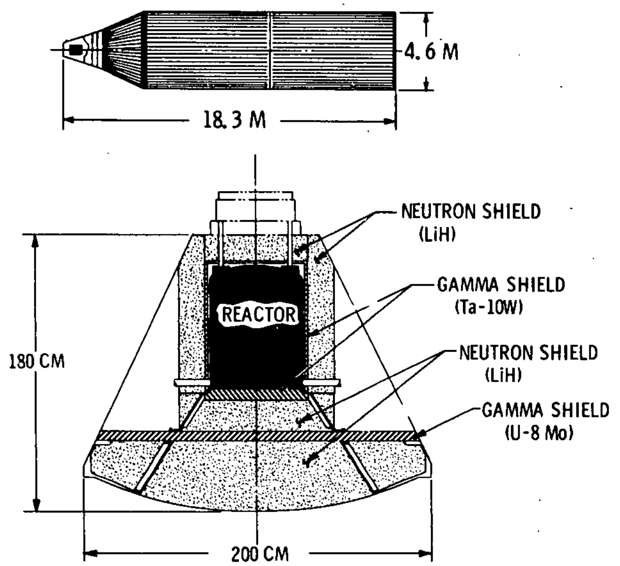
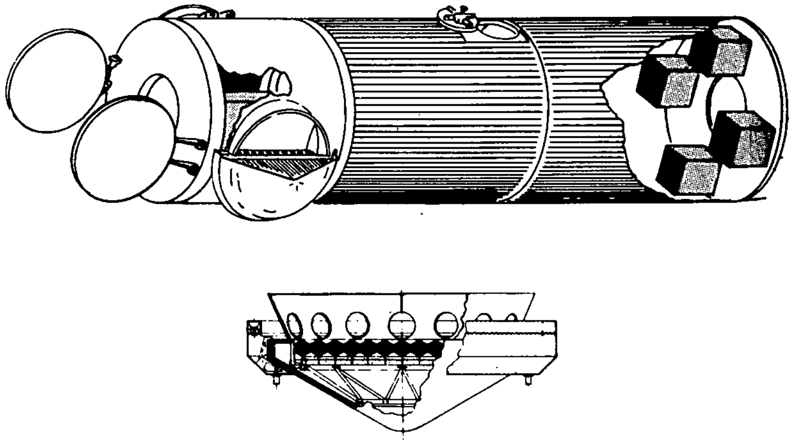


Figure 5. Shuttle Compatible Single Reactor Module

sidered. The common nuclear component to be found in each of the configurations is the Isotope Reentry Vehicle (IRV). The IRV, shown in Figure 6, with the Power Boom configuration, consists of a planar array of plutonium-238 fuel capsules (heat source) contained within a reentry body. The Shuttle could transport one or more IRV's or a total power system, provided integraion requirements are met.

Two small isotope sources were considered, representative of the type that might be transported by the Shuttle in future space operations; the Multi-Hundred Watt (MHW) Radioisotope Thermoelectric Generator (RTG) and the Radioisotope for Thermal Energy (RITE) fuel capsule. The MHW-RTG is designed to deliver 150 w of electrical power from a heat source loading of 2400 w thermal of Pu-238. The MHW could be used singly or in multiples to power unmanned vehicles on deep space missions. The RITE fuel capsule is intended to provide heat for an Environmental Control/Life Support (EC/LS) waste processing system to be used on large manned spacecraft. The capsule used in this unit contains 420 w thermal of Pu-238 and operates at a temperature of 1033°K (1400°F).



DIAMETER	–	2.36 M (92 IN)
MASS	–	1800 KG (3.90 KLBS)
FUEL	–	238 PU O_2
INVENTORY	–	52 KWT (BOL)

Figure 6. Typical Isotope Brayton Module with IRV's

- SAFETY AND HANDLING CAN BE IMPROVED AND SUPPORT REQUIREMENTS IMPOSED ON THE SHUTTLE REDUCED IF A TRANSFER MODULE IS USED TO SUPPORT THE NUCLEAR PAYLOAD WITHIN THE SHUTTLE CARGO BAY.
- NUCLEAR PAYLOADS REQUIRE ENVIRONMENTAL PROTECTION WITHIN THE CARGO BAY. A PROTECTIVE LINER COUPLED WITH INERT GAS CONTAINMENT/PURGING IS RECOMMENDED FOR REACTOR POWER MODULE.
- NO ADDITIONAL RADIATION PROTECTION FOR THE SHUTTLE CREW IS REQUIRED DURING TRANSPORTATION OF REACTOR AND ISOTOPE PAYLOADS UNDER NORMAL CONDITIONS.
- THE SHUTTLE BLAST AND FRAGMENTATION ENVIRONMENT IS RELATIVELY SEVERE DUE TO THE CLOSE PROXIMITY OF THE PAYLOAD TO THE PROPELLANT TANKAGE. CONSIDERABLE BLAST AND FRAGMENTATION PROTECTION IS REQUIRED FOR ISOTOPE PAYLOADS IN THE LAUNCH CONFIGURATION.
- SPACE SHUTTLE/LAUNCH COMPLEX CONFIGURATIONS WHICH POSITION THE NUCLEAR PAYLOAD BETWEEN THE SHUTTLE PROPELLANT TANKS AND THE MOBILE LAUNCHER TOWER PRESENT AN UNDESIRABLE FRAGMENTATION ENVIRONMENT AND SHOULD BE AVOIDED.
- THERMAL CONTROL IS REQUIRED OF LARGE ISOTOPE SYSTEMS DURING ALL PHASES OF THE SHUTTLE/PAYLOAD MISSION. SMALL ISOTOPES MAY HAVE LESS STRINGENT REQUIREMENTS DEPENDING ON PACKAGING CONFIGURATION.
- THE RISK TO THE GENERAL POPULACE IS LOW IN TRANSPORTING EITHER A REACTOR OR ISOTOPE SYSTEM BY THE SHUTTLE. USE OF THE SHUTTLE FOR RECOVERY OF A REACTOR AS CONTRASTED TO A BOOST TO HIGH EARTH ORBIT, CAN REDUCE THE OVERALL RISK BY AT LEAST AN ORDER OF MAGNITUDE.
- THE SHUTTLE PROVIDES CONSIDERABLE CONTINGENCY FLEXIBILITY (i.e., REBOOST TO HIGH EARTH ORBIT, PAYLOAD EJECTION IN DEEP OCEAN AREA, REPAIR OR REPLACEMENT OF FAILED DISPOSAL SYSTEM).

RELATIONSHIP TO FUTURE NASA PROGRAM

The Shuttle Nuclear System Safety Analysis, a part of the Space Base Nuclear System Safety study is intended to provide data for the timely and systematic incorporation of radiological system safety into all applicable phases of NASA's space program with particular emphasis on the Space Shuttle. The key candidate areas for programmatic applications are discussed below.

SPACE SHUTTLE PROGRAMS

The study provides a preliminary assessment of the Shuttle integration and operational considerations in support of nuclear payloads. Crew radiation protection requirements are identified. A terrestrial safety analysis of ZrH reactor and isotope-Brayton power module/Shuttle missions was performed to identify the highest risk areas in the mission. Nuclear Safety related design and operational guidelines are presented for application to NASA's Shuttle program.

MANNED EARTH ORBITAL SPACECRAFT PROGRAMS

Shuttle/nuclear payload docking techniques are presented which consider replacement and retrieval of spent modules as well as initial installation to an earth orbiting base. Emphasis is on minimizing crew doses, visual capability and maintenance of positive control of the payload at all times.

NASA/AEC REACTOR AND ISOTOPE PROGRAMS

Results of the integration and operational evaluation and terrestrial nuclear safety analysis of Shuttle/nuclear payload missions can be applied in future space reactor and isotope programs involving the Space Shuttle. Design and operational features which can eliminate or reduce hazards and risks to hardware and personnel are identified.

INTERPLANETARY SPACE PROGRAMS

Many of the guidelines established and design features identified for the Shuttle transport of nuclear payloads are applicable to Shuttle launched interplanetary programs employing isotope or reactor power systems and nuclear propulsion stages.

PROGRAM PLANNING

The study assists in identifying safety related program requirements for planning and support of future Shuttle

missions employing nuclear hardware. Of particular interest is the impact on support facilities and operations at KSC and the requirements of the recovery and radiological control teams at the nuclear hardware impact points and Shuttle landing sites.

SPACE NUCLEAR SYSTEM DESIGN AND SAFETY STUDIES

An extensive review of space and nuclear system design and safety literature was performed. Documents were categorized as to technical content and source, and completed ASRDI forms were submitted to NASA's Aerospace Safety Research and Data Institute in Cleveland, Ohio. This data along with data in Volume VII Part 1 of this study, provides an excellent source index of nuclear system safety related literature.

PACKAGING AND INTEGRATION

Various integration considerations play an important role in implementing the nuclear safety of the Shuttle mission. The Shuttle cargo bay dimensions, payload mass limits, and the center of gravity envelope are the prime Shuttle-imposed constraints on a reactor power module. These constraints limit the total radiator area available, the shield and reactor mass; and therefore have a direct impact on reactor power system growth capability.

Figure 7 illustrates the principal safety related integration requirements. A summary of these requirements is presented in the following paragraphs.

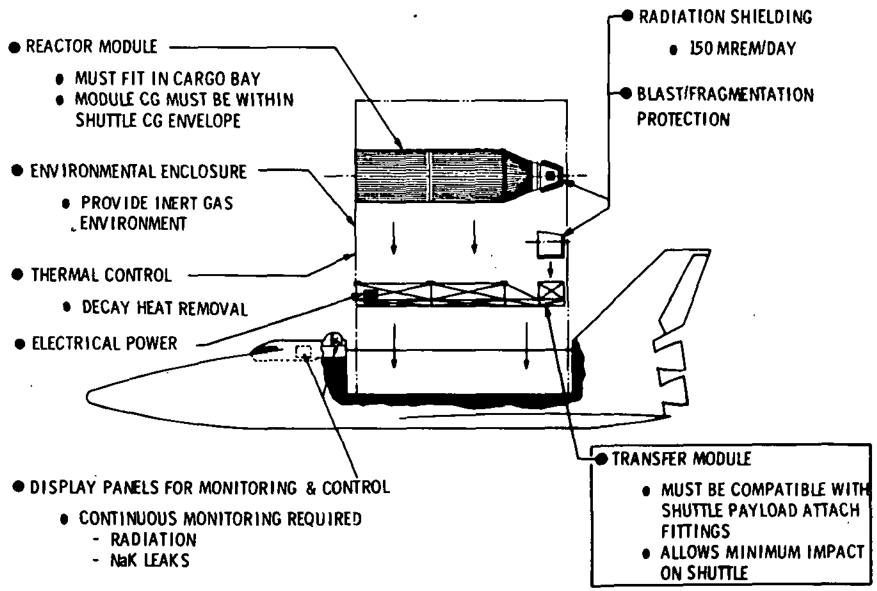
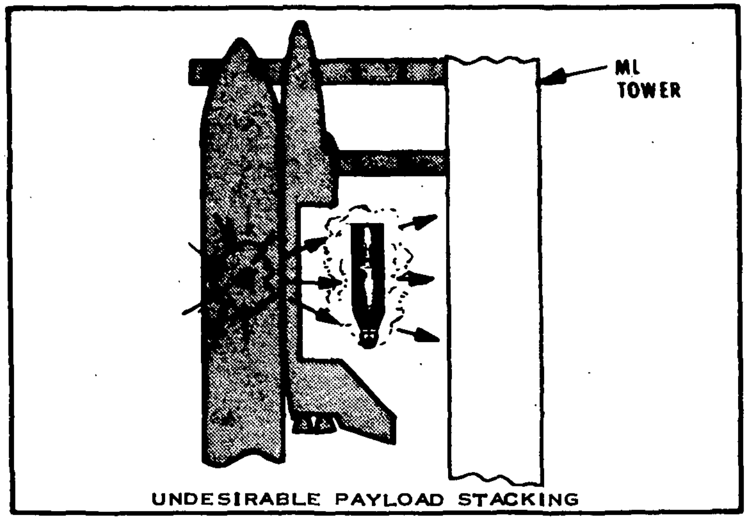


Figure 7. Reactor Packaging/Shuttle Integration

- Radiation Protection. No additional radiation protection is required for the crew with a pre-operational reactor placed in the cargo bay. A similar conclusion can be made for the post-operational case provided the reactor is placed toward the rear of the Shuttle cargo bay not prior to ten days after reactor shutdown. Adverse radiation effects on Shuttle subsystems are not expected, however, integrated doses over many nuclear missions would merit further consideration (material selection and location of solid state electronics, film, etc.).

- Blast and Fragmentation Protection. The Shuttle presents a severe blast and fragmentation environment (Figure 8). Little or no additional blast and fragmentation protection is required of an unoperated reactor, however, the positioning of the payload away from the Mobile Launcher tower to provide an unobstructed ejection path will reduce fragmentation damage. Design for intact impact of the core in the post-operational case could be required due to the potential high fission product inventory.



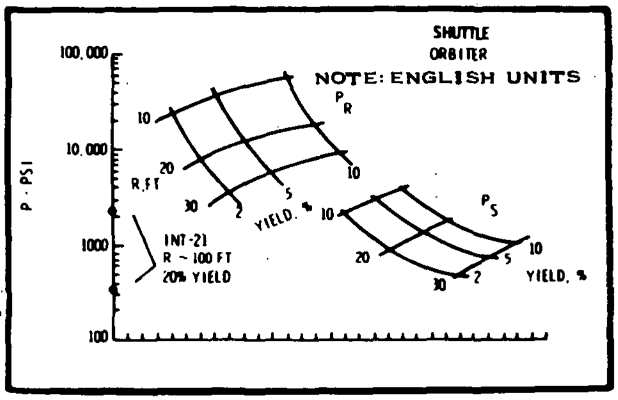


Figure 8. Shuttle Explosive Overpressure and Blast Environment

- Environmental Protection. The cargo bay should be capable of preventing LO_2 and LH_2 vapors from entering. Double containment or an inert cover gas "blanket" around the power module (particularly around its liquid metal components) will reduce liquid metal hazards.

- Thermal Control. Temperature transients within the cargo bay could cause NaK freeze up. Auxiliary heating may be required to resolve this problem. If it were found necessary to place a reactor power module into the cargo bay immediately after reactor shutdown, up to 1 kWt cooling could be required to remove decay heat. A transfer of this nature should be avoided and a waiting period of at least 2 days planned to allow for thermal cool down.

- Payload System Status and Controls. It is estimated that the receipt of 80 data points and displays (periodic and continuous monitoring), and sending of 25 control signals are required of Shuttle systems.

- Electrical Power. A maximum of 1 kw electrical power is required for 2 days, if decay heat thermal control is necessary. Other electrical requirements should not exceed 0.5 kw total. Either power from batteries or the Shuttle Electrical Power System could be considered.

- Attachments and Payload Handling. The power/module center of gravity may be located toward the reactor/shield and away from the primary attach points. Additional support may be required to prevent longitudinal buckling. The use of a cradle type "transfer module" (see Figure 7), which supports the reactor and in turn is placed in the cargo bay can significantly reduce Shuttle integration requirements and increase safety during handling operations. A capability of emergency payload ejection into a deep ocean area (during launch or end-of-life recovery operations) could be provided by the "transfer module".

TRANSPORTATION OPERATIONS

A ZrH reactor power module presents a relatively low nuclear hazard prior to orbital operations if pre-flight criticality tests are limited to low power levels. After operations in orbit, the reactor could have a potentially large core fission product inventory, thus increasing the nuclear hazards during retrieval, disposal or recovery operations which would be performed by the Shuttle.

Several power module ground handling and orbital transfer techniques were defined. Figure 9 illustrates potential transfer techniques during prelaunch. The liquid metal hazards may be the dominant consideration. Installation at the launch pad is preferred in that this operation can occur late in the countdown. This approach would reduce the possibility of prelaunch accidents that could involve the reactor and eliminates the possibility of potential nuclear related accidents in the VAB and the necessity of providing the nuclear support, plans and hardware for that facility.

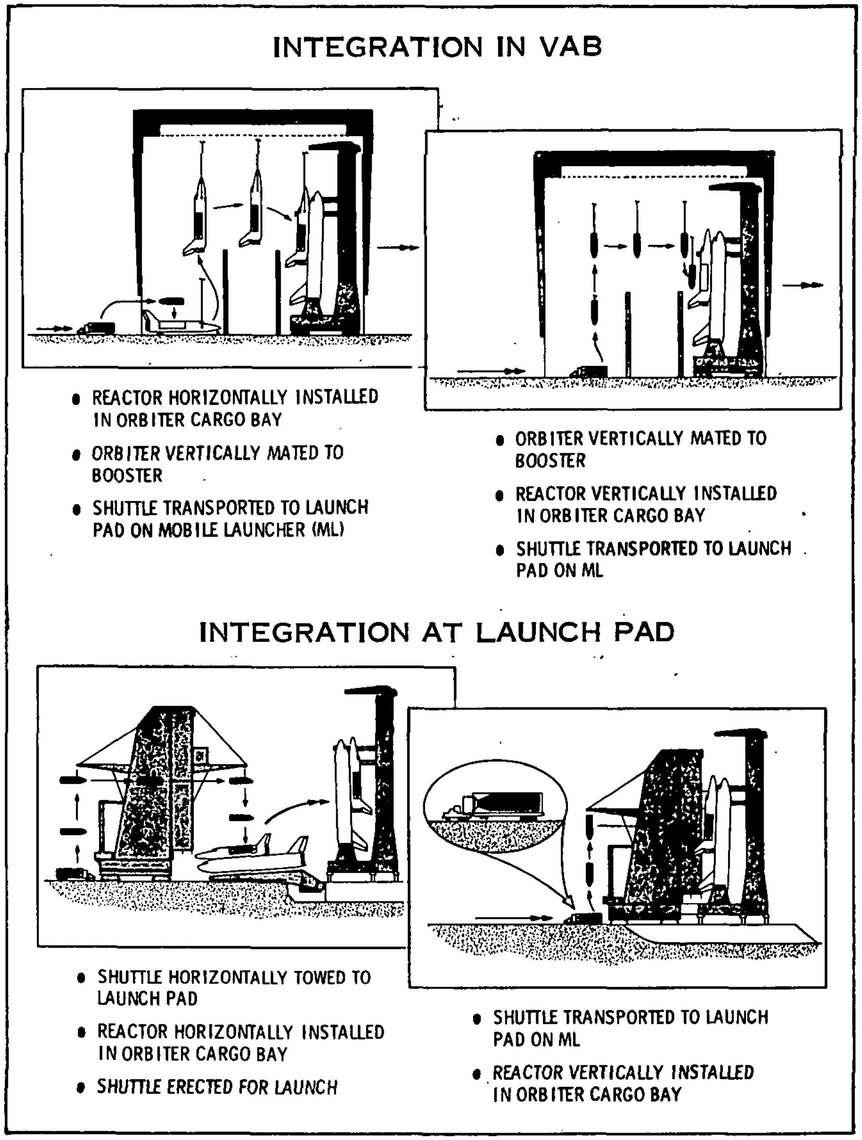


Figure 9. Reactor Integration with Shuttle

A configuration which permits location of the reactor in the Shuttle cargo bay away from the Mobile Launcher tower is preferred to reduce fragmentation damage potential.

Power module replacement and retrieval missions take on added complexity since two reactor power modules must be handled - the replacement power module that is brought up in the Shuttle and the "spent" module that is to be replaced.

Several orbital replacement and retrieval/recovery techniques are shown in Figure 10 which employ three different payload transfer devices: (1) manipulator arms (articulation), (2) flexible tunnel (rotation, and (3) scissors platform (translation).

The radiation dose to the Shuttle crew from a shutdown "spent" power module after 5 years operation at 125 kWt requires that a minimum wait time of at least 10 days be allotted for the dose rate to go below the maximum allowable 150 mrem/day. Crew gamma shielding would be required if the wait time were reduced. The flexible tunnel approach would be unacceptable for the transport of a spent module unless a rotational trunnion were used to position the shield in the aft section of the cargo bay.

Additional analysis is required to determine the best approach when nuclear safety parameters such as crew

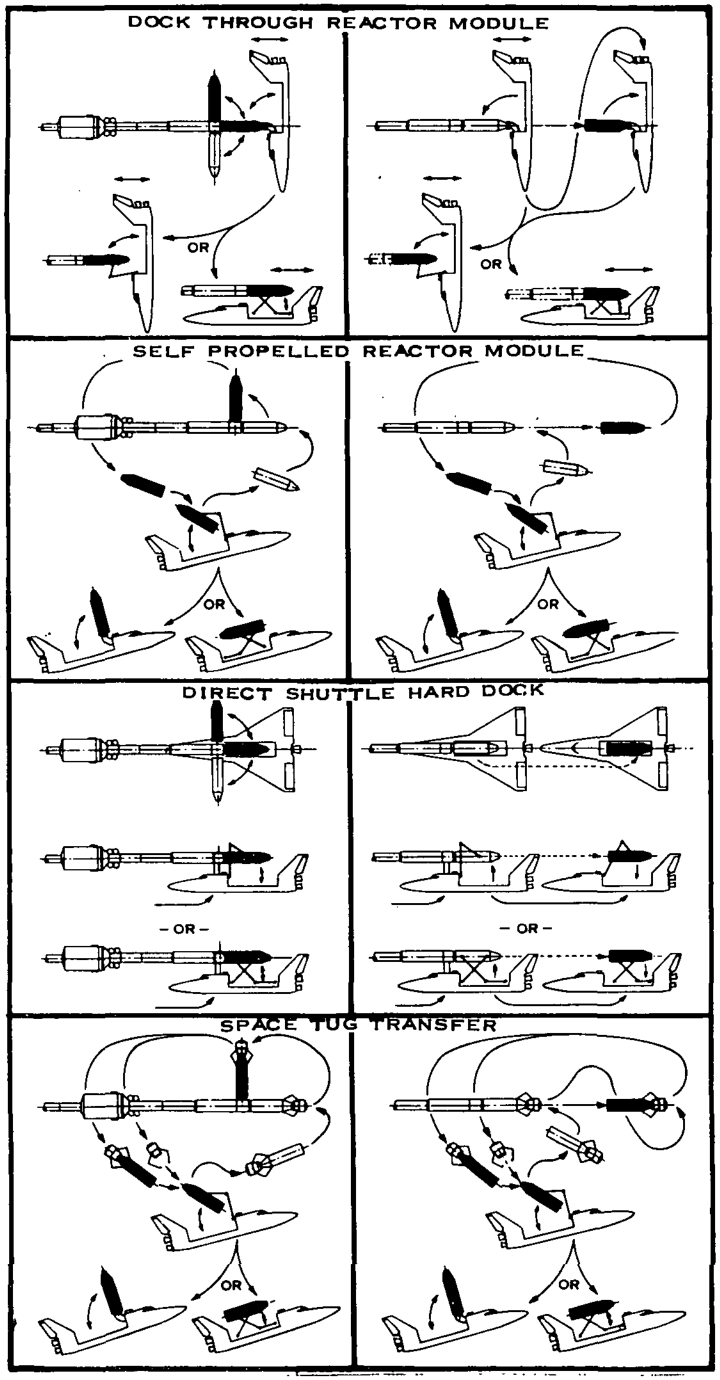


Figure 10. Replacement/Retreival Schemes

dose rates, visibility and positive control are considered. There is no need for recovery of the radiator and power conversion systems. In fact, a liquid metal radiator adds to the non-nuclear hazards during recovery. Techniques should be developed to recover only the reactor/shield.

CONTINGENCY OPERATIONS

The implementation of contingency operations could eliminate or substantially reduce the adverse effects on the mission and the risks to personnel resulting from accident or failure situations. The contingencies addressed in the study include:

- Liquid metal leak detected within cargo bay on launch pad
- Detected failure of power module during launch ascent or rendezvous
- Shuttle failure during ascent
- Failure of Shuttle doors to open prior to payload emergency ejection
- Failure to remove power module from cargo bay or to dock to Space Base
- Shuttle retrieval, disposal or recovery of a damaged power module
- Disposal failure resulting in short life orbit detected during descent from orbit

The following provisions are considered key to the implementation of contingency plans:

- Double containment - use of a positive pressure liner
- Back-up Shuttle support and rescue
- Liquid metal fire protection equipment within Shuttle
- A strap-on disposal system
- Fault detection of Shuttle and power module failures during flight
- Ejection of payload into deep ocean areas
- Clean, obstruction free cargo bay interior surfaces

PACKAGING AND INTEGRATION

Packaging and integration for the transport of an isotope-Brayton power module presents several different safety considerations than does a reactor. No liquid metal hazard exists with an isotope-Brayton power module as contrasted with a reactor power module. Coolant loops generally contain relatively non-hazardous organic fluids. Important differences occur in the Prelaunch Phase where an isotope heat source presents continuous thermal and radiation hazards. The isotope heat source must be cooled at all times prior to lift-off. In addition, it is a constant source of neutron radiation with increased gamma radiation occurring as the isotope decays, reaching a peak after 18 years.

The principal safety related Shuttle integration considerations for transport of the isotope heat source are illustrated in Figure 11, and are summarized below:

- Radiation Protection. No auxiliary shielding is required for the Shuttle orbiter crew for normal operations provided the base of the conical heat source is parallel to the cargo bay and at least 5.5 m from the nearest crew member.

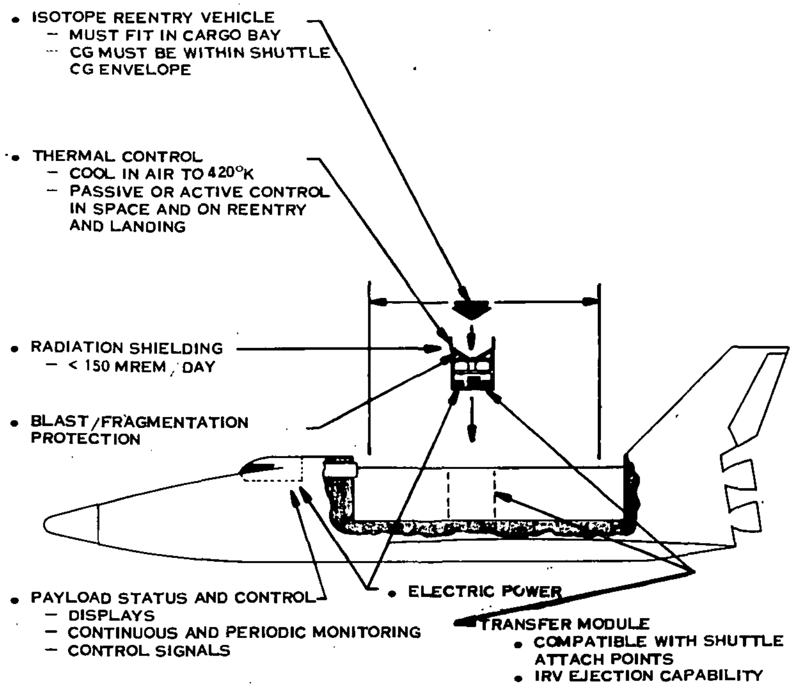


Figure 11. Isotope Reentry Vehicle Packaging/ Shuttle Integration

- Blast and Fragmentation Protection. Blast and fragmentation protection must be provided while in the Shuttle. The most severe problem exists at launch due to the large amount of propellant. The payload must be provided an unobstructed ejection path, preferably into an ocean or remote area, should a launch explosion occur.

- Thermal Control. Thermal control of an isotope heat source is required within the Shuttle to maintain acceptable capsule temperatures.

Where an entirely passive system is not feasible, redundant and/or back-up systems as shown in Figure 12, must be provided. The design of the blast and fragmentation shield is intimately involved in thermal control design.

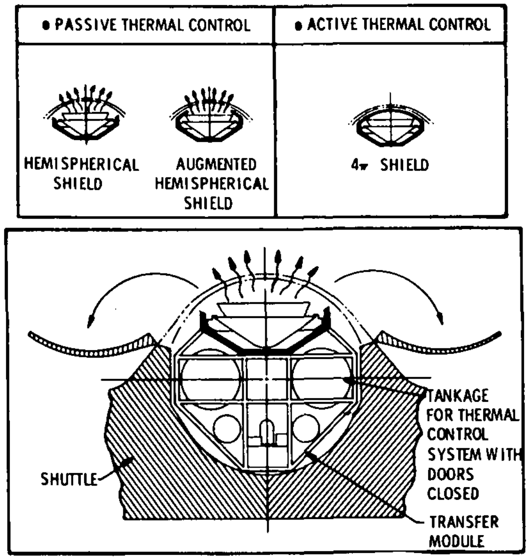


Figure 12. Thermal Control Concepts

- Payload System Status and Controls. It is estimated that the receipt of a maximum of 62 data points and display functions (periodic and continuous monitoring), and sending of 32 control signals are required of Shuttle systems.

- Electrical Power. It is estimated that a maximum of 300 w of electrical power is required, and the total energy requirement will not exceed 23 kw-hr for support of the thermal control system. This power could be supplied by batteries.

- Attachment and Payload Handling. The use of a supporting cradle "transfer module" will greatly reduce Shuttle interface requirements and provide possible ejection capability over the continental shelf or deep ocean areas if diagnostic data during ascent and landing warrant it.

TRANSPORTATION OPERATIONS

The transport operations involving the Isotope Reentry Vehicle (IRV) are similar to those of a reactor power module with notable exceptions described in the following paragraphs.

The initial interaction between the IRV and the Space Shuttle occurs when it is installed in the Shuttle cargo bay. Due to the radiation and thermal environment characteristics of the heat source, integration with the Shuttle at the launch pad should occur as late in the countdown as possible.

It is assumed that the IRV would be placed in an IRV Transfer Module prior to installation in the Shuttle cargo bay. The transfer module will serve to protect the IRV, simplify handling and provide a mode of thermal control. The isotope-Brayton Power Conversion System (PCS) can also be installed in a transfer module. Depending

on the logistics requirements and design configuration, the PCS can be transported with the IRV or by a separate Shuttle launch. Launch of multiple units of either the IRV or PCS are possible.

During a normal launch ascent, the heat generated by the isotope fuel is largely taken up by the heat source structure. Only a slight increase in temperature is expected in the approximate 8 minutes of flight, prior to opening of the cargo bay doors. The expected temperature profile of the heat source is shown in Figure 13 along with the anticipated increase in temperature if the doors fail to open.

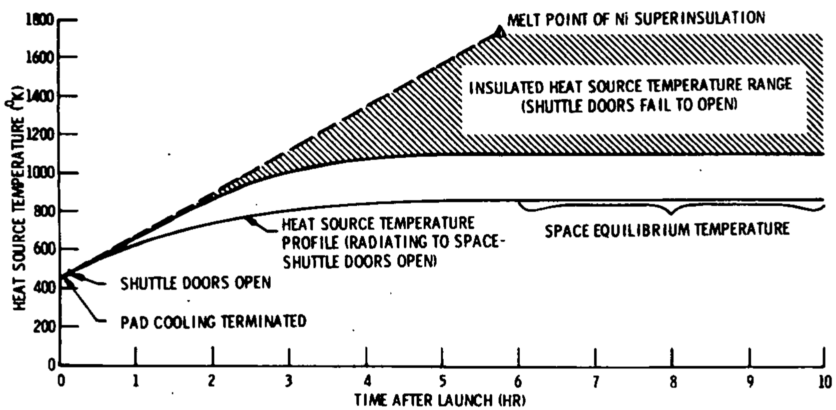


Figure 13. Estimated Heat Source Temperature Profile

Several approaches to delivery, transfer, retrieval and recovery were defined, the majority of the techniques closely paralleling those described for the reactor power module. Recovery of an IRV is assumed to be a prime objective.

Three transfer schemes associated with the delivery of an IRV to the Space Base are detailed in Figure 14. All three involve the use of manipulators and in each case operations are performed without EVA. Special features should include: (1) the limiting of travel so that an IRV cannot be placed adjacent to Shuttle or Space Base surfaces, (2) side-on positioning with respect to the crew, (3) visual contact during operations, and (4) all power system assemblies secured at all times.

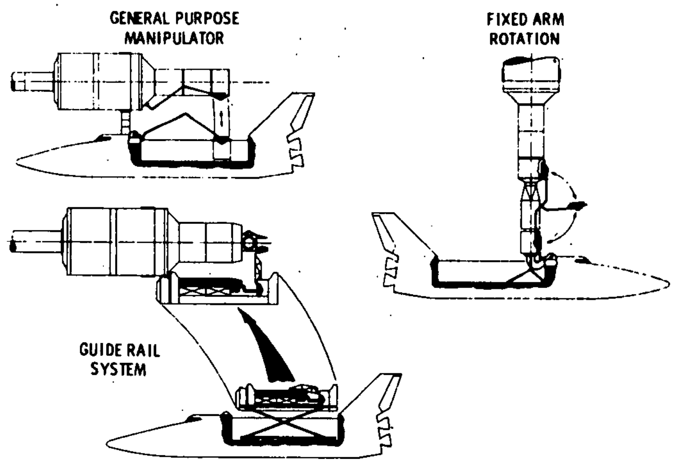


Figure 14. IRV Transfer Schemes

Retrieval and recovery operations are similar to ascent and rendezvous. However, during descent, Shuttle doors would remain closed and active cooling of the IRV would be required.

CONTINGENCY OPERATIONS

The contingency modes available in a Shuttle mission transporting an isotope heat source(s) were found to be similar to those described for a reactor power module. However, no liquid metal hazards exist. Other notable differences are due to the thermal hazard presented and the potential worth and reusable characteristics of the isotope, placing added emphasis on recovery.

The contingencies addressed in the study include:

- Loss of heat source cooling on the launch pad
- Launch pad explosion and fire
- Failure of cargo bay doors to open on ascent
- Retrieval and recovery of a damaged heat source
- *Recovery versus disposal options*

The following provisions are considered key to the implementation of contingency plans:

- Propellant vapor not permitted to enter cargo bay
- Redundant heat source cooling systems available on the launch pad and in flight
- Extensive blast and fragmentation shielding
- Launch configuration permits an unobstructed blast ejection path to carry heat source out of the fireball perimeter
- Ejection of the heat source into an ocean area (preferably where recovery is probable)
- Clean, smooth, obstruction free cargo bay interior surfaces to enhance decontamination
- Sealed crew compartment to prevent radioactive vapor from entering
- Recovery aids

PACKAGING AND INTEGRATION

The Space Shuttle may be employed to transport small radioisotope devices (< 2500 w thermal) to and from earth orbit. The characteristics of the various isotope devices which could be used on a Space Base can vary considerably. Two typical isotopes considered in the study are the Multi-Hundred Watt Radioisotope Thermo-electric Generator (MHW), and the Radioisotope for Thermal Energy (RITE) heat source for the Integrated Waste Management System. The MHW's application in conjunction with the Space Shuttle would typically be to power subsatellites or unmanned deep space probes that are carried into earth orbit in the cargo bay of the Shuttle. The RITE source may be transported within a logistics pallet.

Characteristics of these two small isotopes as compared with an IRV are shown in Figure 15. The fuel loading of the MHW is considerably less than the IRV, although the radiation levels are not as markedly different. This is due to the use of a Plutonium isotope in the IRV which is depleted in 0_{17}, 0_{18} and Pu-236, considered an important safety feature for manned applications where considerable quantities of isotope are required .

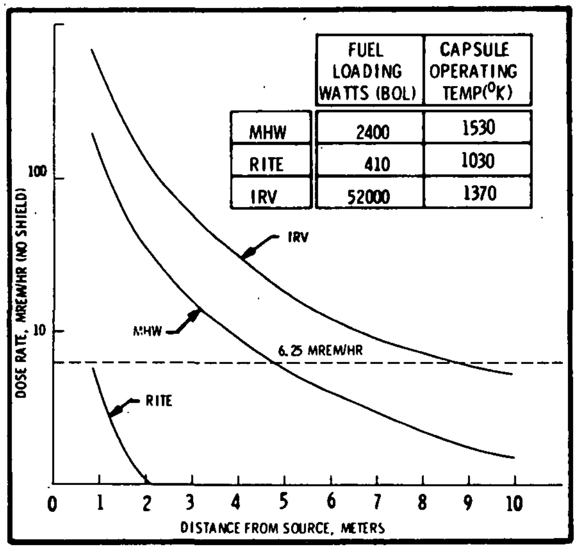


Figure 15. Isotope Heat Soucre Comparison

The interfaces to be considered for small isotopes are essentially the same as those for the IRV, however, the approach to satisfying the interface requirements may be different. Blast, fragmentation, fireball, and re-entry protection must be provided for single and multiple heat source configurations. In some instances, the heat source may not require additional cooling, the emphasis placed on the maintenance of allowable temperatures of the spacecraft components or equipment in the logistics pallet.

TRANSPORTATION OPERATIONS

The Shuttle provides the prime mode of delivery and retrieval of small isotopes, although, some small isotopes may be initially launched on-board Space Base Modules. It is expected that during a Space Base mission and at the end of mission "close out", isotope heat sources and other non-expendable cargo would be transferred to the Shuttle and returned to earth.

This transfer technique involving the use of a logistics pallet is shown in Figure 16. The isotope heat source(s) may only be a part of the total equipment in the logistics pallet. Radiological safety requirements, (crew dose limit, and equipment limits) are dependent

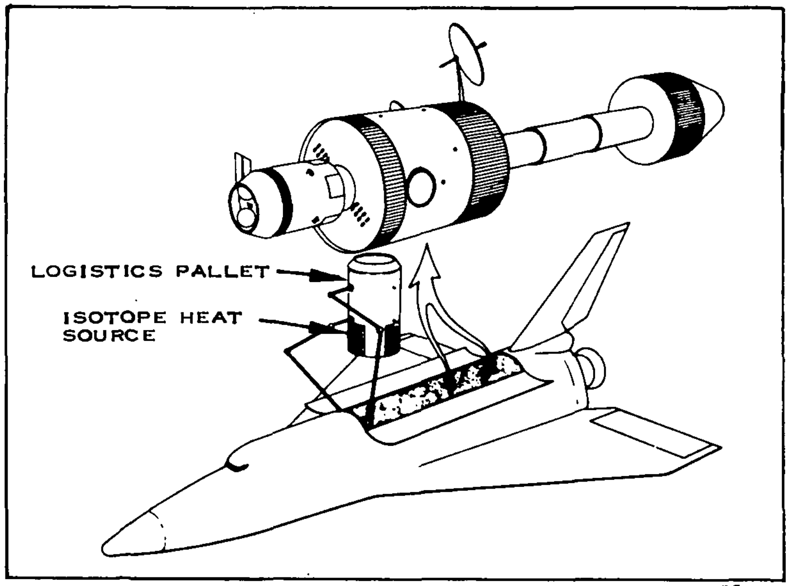


Figure 16. Rite Heat Source in Logistics Pallet

on the type of and quantity of isotope used and the location with respect to the crew and equipment.

The Shuttle could be used to place an RTG and Spacecraft or Space Base subsatellite into earth orbit. This transportation mission is illustrated in Figure 17.

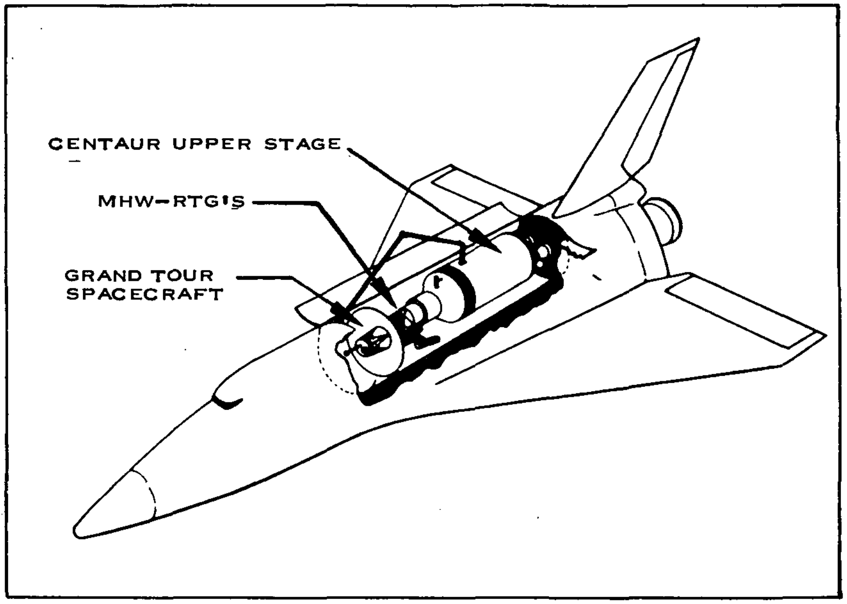


Figure 17. MHW on Grand Tour Spacecraft

The Shuttle is shown, placing a MHW-RTG powered Grand Tour Spacecraft and a Centaur booster stage into earth orbit prior to insertion of the payload into a deep space trajectory. Additional crew shielding may be required with this configuration.

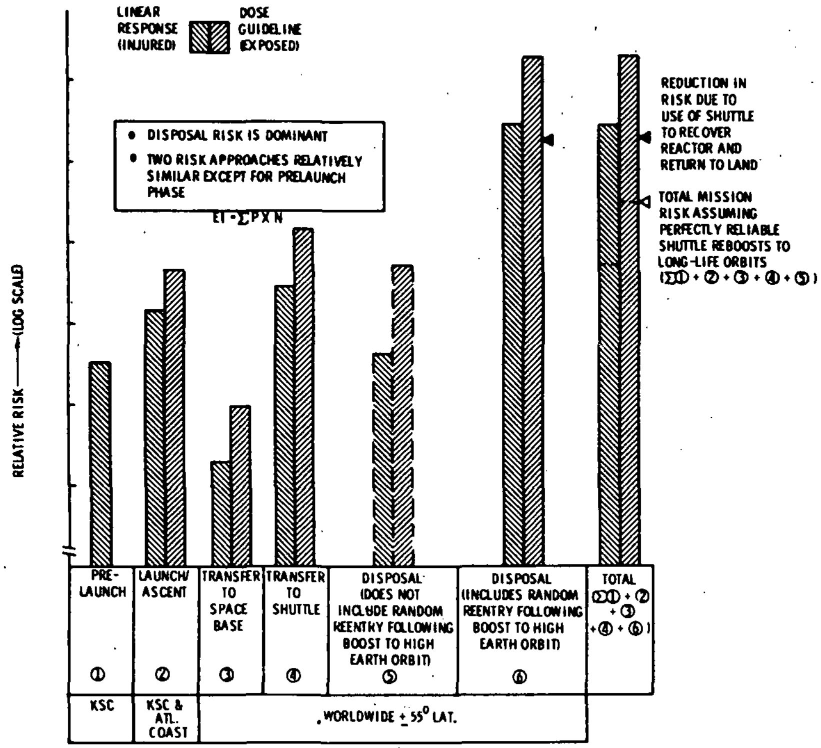
A preliminary terrestrial safety analysis (safety of the earth's general populace and ecology) was performed for Space Shuttle missions involving the ZrH reactor power module and the IRV. The primary objective of the analysis was to evaluate the extent and impact of identified nuclear hazards on the general earth's populace. Most of the Space Shuttle launch trajectory is over water, except for a brief land overflight of Nova Scotia and Newfoundland. The descent trajectory for a KSC landing is also over water, except for land overflight of the southernmost part of Mexico and central Florida. Therefore hazards to the general populace are minimized. Detailed analyses and results are presented in Volume IV, Part 2 (72SD4201-4-2).

REACTOR TERRESTRIAL SAFETY ANALYSIS

Two approaches are used for the reactor evaluation: (1) Dose Guideline and (2) Linear Response. In the dose guideline approach, all individuals exposed to the dose guideline value or above are considered exposed. This risk approach results in the number of exposures from an accident, but does not continue on to the biological end-point to indicate the number of resulting injuries.

The linear response approach is based on the hypothesis of a linear relationship between biological effect and the amount of radiation dose which is supported by the latest existing data on human and mammalian radiation response. Both risk approaches provide relative data from which priorities can be placed to enact design and operational features to reduce overall mission risk.

The risk analysis summary for the Shuttle/Reactor payload mission (Figure 18) indicates the relative exposure indices for each phase of the mission using the linear response and the dose guideline approach. The overall mission risk is low. The two risk analyses approaches result in the same relative risk ranking; the dominant risk occurring in the Disposal Phase. The Disposal Phase risk essentially accounts for the total mission risk. Also indicated is the hypothetical mission risk assuming perfectly reliable Shuttle reboosts to long-life orbits. Analysis has shown that a Shuttle orbiter recovery and return to land would reduce the risk significantly (approximately one order of magnitude). Permanent reactor shutdown prior to disposal orbit insertion and prevention of reactor excursions would also contri-



Phase	Highest Risk Accident	Cause	Safeguards
Prelaunch	Launch Pad Explosion and Fire • Destructive Excursion	• Propellant Ignition During Fueling or Countdown	Control Drum Lockout Device
Launch and Ascent	• Orbital Rendezvous Abort • Earth Impact of Shuttle Containing Reactor	• OMS Failure • G&C Failure	Control Drum Lockout Device
Reactor Transfer to Space Base	• Failure to Mate Reactor to Space Base • Reactor not Recovered • Reactor Reentry and Earth Impact	• Reactor Docking Port Failure • Transfer Mechanism Failure	Control Drum Lockout Device
Reactor Transfer to Shuttle	• Shuttle Collision with Space Base • Uncontrolled Orbiter Reentry • Earth Impact of Shuttle Containing Reactor	• G&C Failure	• Maximize Reactor Intact Impact Capability • Provide Tracking Capability
Reactor Disposal	• Successful Boost to 835 KM Disposal Orbit • Eventual Reentry and Earth Impact after 250 Years	• None	• Permanent Reactor Shutdown Prior to Disposal Orbit Insertion • Provide Tracking Capability • Shuttle Recovery and Return to Land

Figure 18. Reactor Accident Evaluation & Relative Risk Summary

bute to reducing the risk. There would essentially be zero risk associated with the Launch/Ascent Phase if reactor excursions can be prevented.

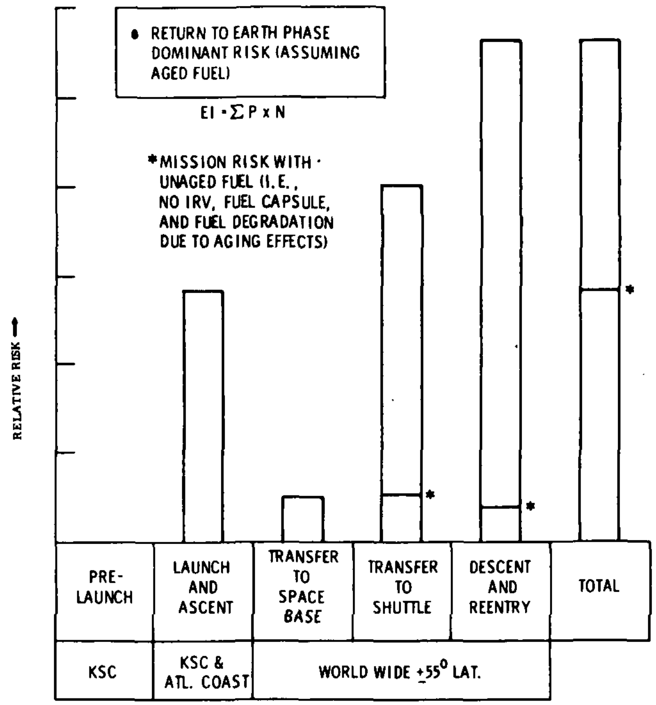
The linear response method results in an exposure index value in the Prelaunch Phase while the dose guideline method does not. The linear response model considers exposures to zero dose levels and therefore results in an exposure index value based on some probability of injury event at low radiation levels. The linear response method may also be used to indicate the degree of injury. By selection of the proper radiation exposure threshold, the number of acute exposures in which clinical symptoms of the radiation exposure are evident, can be determined.

ISOTOPE TERRESTRIAL SAFETY ANALYSIS

For the isotope-Brayton risk evaluation, only the dose guideline approach is utilized because data on the response from deposited plutonium in the lung as a function of radiation level is not available. Therefore, dose guideline values for the plutonium affected organs (lung, bone and whole body) are used in the evaluation.

The aging effect on the isotope reentry vehicle (IRV), fuel capsules, and the plutonium fuel after ten years of use on the Space Base is considered to have a significant impact on safety. Recent data appears to indicate that aging effects may not be as pronounced as previously assumed and a reduction of the fuel release source terms may result. The assumed degradation due to aging would reduce the IRV and fuel capsule survival capability. This factor accounts for the higher failure probabilities for atmospheric reentry accident environments.

The risk analysis summary (Figure 19) for the Space Shuttle/isotope-Brayton nuclear payload mission shows that the IRV Recovery (i.e., descent and reentry) Phase accounts for practically the entire mission risk (assuming aged fuel). Figure 19 indicates that up to a three order of magnitude reduction in mission risk may be achieved assuming no adverse aging effects on the reference isotope system. Particular emphasis on safeguards, in particular aging, is therefore required in the final mission phases to improve mission safety.



Phase	Highest Risk Accident	Cause	Safeguards
Prelaunch	Launch Pad Explosion and Fire	Ignition of Propellant During Fueling or Countdown	• IRV Ejection Mechanism
Launch and Ascent	• Orbital Rendezvous Abort • Earth Impact of Shuttle Containing IRV	• OMS Failure • G&C Failure	• IRV Ejection Mechanism • Maximize IRV Impact Capability
Transfer to Space Base	• Shuttle Collision with Space Base • Shuttle-Earth Impact with IRV	• G&C Failure	• IRV Ejection Mechanism • Maximize IRV Intact Impact Capability
Transfer to Shuttle	• Shuttle Collision with Space Base • Shuttle-Earth Impact with IRV	• G&C Failure	• IRV Ejection Mechanism
	• Failure to Remove IRV from Docking Port • IRV Ejected from Space Base	• Orbiter Transfer Mechanism • IRV Release Mechanism	• Maximize Intact Impact Capability of Aged System
Descent and Reentry	• Shuttle Crash While Proceding to Landing Site	• Landing Gear Failure • Structural Failure During Reentry	• IRV Ejection Mechanism • Maximize Intact Impact Capability of Aged System

Figure 19. IRV Accident Evaluation & Relative Risk Summary

NUCLEAR SAFETY GUIDELINES SUMMARY

A number of guidelines have resulted from the study and are delineated in Volume V Part 2 72SD4201-5-2. Reference shall be made to this document and supporting data in the implementation of Shuttle related nuclear safety guidelines in future Manned Space Flight programs. Guidelines are summarized in accordance with the following hazard reduction sequence:

- Design Features, Table 3
- Safety Devices, Table 4
- Warning Devices, Table 5
- Special Procedures, Table 6

Table 3. Design Features

- Provide multiple and independent radiation monitoring equipment in the Shuttle.
- Provide multiple and independent system monitoring and control equipment in the Shuttle.
- Provide a clean, smooth surface cargo bay interior.
- Consider uncooperative "tumbling" payload retrieval with Shuttle.
- Provide maximum Shuttle contingency stay times in orbit of at least 20 days.
- Provide maximum separation distance between Shuttle crew and nuclear payload.
- Provide for free, unobstructed ejection path at the launch pad.
- Consider use of a "transfer module" to improve safety in handling.
- Provide for intact reentry and impact of nuclear hardware (consider use of crush-up material in Shuttle).
- Provide for double containment of liquid metal systems (possible use of inert-gas pressure liner)
- Provide blast overpressure and fragmentation protection.
- Provide Shuttle fireball protection for nuclear payloads
- Provide tracking devices on nuclear payloads
- Consider retrieval/recovery of reactor and shield only.
- Provide isotope thermal control (cooling) capability throughout all phases of the Shuttle mission.
- Provide isotope heat source cooling to $420^{\circ}K$ during prelaunch.

Table 4. Safety Devices

- Provide compatible liquid metal fire protection and fighting capability in the Shuttle and at launch and landing sites.
- Provide capability to defuel the Shuttle in nuclear emergencies on the launch pad.
- Provide dry N_2 purging capability of the Shuttle cargo bay volume on the launch pad.
- Consider use of a back-up Shuttle to support repair of a failed Shuttle or transfer or retrieval of the payload in orbit for the continuance of the mission.
- Provide Shuttle radiation and liquid metal decontamination capability at the launch and landing sites.
- Provide tracking and location aids for rapid land and water recovery.
- Provide for positive and permanent reactor shutdown prior to Shuttle retrieval and recovery.

Table 5. Warning Devices

- Provide rapid response fire detection and alarm systems for liquid metal fires on the Shuttle.
- Provide capability of detecting and alerting the Shuttle crew of payload and Shuttle failures and hazardous conditions during transport.
- Provide crew/personnel dosimetry and radiation instrumentation in Shuttle cargo bay and crew.
- Provide means for warning of imminent collisions with orbiting vehicles.
- Provide proper governmental authorities with technical data for advanced warnings and preparations of impending ground impact of Shuttle with nuclear payload.

Table 6. Special Procedures

- Provide training and procedures in the use of radiation monitoring equipment.
- Maintain administratively controlled areas with a minimum radius of approximately 13 km and exclusion areas of 4 km radius from launch site.
- Provide installation, retrieval and maintenance procedures that do not require breaking or opening of Nak loops.
- Establish emergency procedures and decisions (contingency plans) for emergency situations.
- Prohibit launch during unsatisfactory weather conditions, particularly with winds blowing towards populated areas.
- Minimize overflight of land and continental shelf areas.
- Provide nuclear cargo transfer operations that do not involve EVA.
- Provide direct visual or TV coverage of transfer operations.
- Minimize the crew and support personnel dose rate.
- Provide rendezvous and docking/transfer operations that make maximum use of "spent" reactor shadow shielding.
- Allow at least 10 days after reactor shutdown before enacting Shuttle retrieval/replacement operations.
- Provide minimum 100 year orbital lifetime for spent reactor in high earth disposal orbit.
- Provide procedures for ejection of the payload over deep ocean or continental shelf areas.
- Install isotope heat sources at last practicable point in Shuttle launch countdown sequence.
- Consider touchdown area remote from inhabited facilities.

A review of the analyses and results of the study was made to identify technical areas where significant additional research and development are required. Several of the key areas of technology are briefly discussed below.

BLAST AND FRAGMENTATION PROTECTION

The Shuttle blast and fragmentation environment in the vicinity of the cargo bay is severe. Blast and fragmentation data should be obtained and concepts evaluated and tested to provide the necessary protection required of isotope and reactor payloads.

ISOTOPE THERMAL CONTROL SYSTEMS

Thermal control requirements of isotope heat sources within the Shuttle cargo bay necessitate the design and development of failproof/redundant systems that will provide adequate cooling throughout the Shuttle mission.

PAYLOAD INERT GAS PROTECTIVE LINER

Liquid metal and radiological hazards resulting from payload damage can be reduced by use of a protective liner which can envelope the payload within the cargo bay. The payload would remain within the liner upon Shuttle landing and removal from the cargo bay. Conceptual design and feasibility studies are required.

PAYLOAD TRANSFER MODULE

The use of a transfer module appears to offer several advantages including improved nuclear safety in handling and reduction of the design impact on the Shuttle and nuclear payload. Support requirement trade-offs and design studies should be performed.

PAYLOAD EJECTION

Results of the preliminary analysis indicate that consideration should be given to payload ejection into continental shelf or deep ocean areas pending certain emergency situations during ascent and descent. A risk/benefit study should be made and concepts formulated which provide minimum impact on the Shuttle.

The use of the transfer module to support the ejection requirement should be considered.

GRAPPLING OF UNCOOPERATIVE NUCLEAR MODULES

Conditions can arise whereby a nuclear module could become free from the Shuttle or Base while in orbit. Random reentry should not be permitted - therefore controlled retrieval and recovery by the Shuttle may be required. Techniques should be formulated for the grappling of tumbling nuclear modules, transfer to the Shuttle cargo bay and return to earth.

GENERAL ELECTRIC

Space Division / Headquarters: Valley Forge, Pennsylvania ☐ Daytona Beach, Fla. ☐ Cape Kennedy, Fla. ☐ Evendale, Ohio ☐ Huntsville, Ala. ☐ Bay St. Louis, Miss. ☐ Houston, Texas ☐ Newport Beach, Calif.